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OPTIMAL THERMAL GRADIENT FOR MAXIMUM FLUX EXPULSION IN 600 ºC HEAT-TREATED CEBAF 12 GEV UPGRADE CAVITIES*

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Abstract

We present results on measurements of flux expulsion in CEBAF 12 GeV upgrade cavities that were made from high purity fine-grain niobium. These cavities were heat treated in vacuum at 600 ºC, a departure from today's more common treatment temperature of 800 ºC. An optimal thermal gradient ~ 10 K/m is observed at which the ordinary flux expulsion indicator B_{sc}/B_{nc} is maximal. Surprisingly, that maximal value reaches or exceeds the theoretically calculated limit of 1.23, suggesting perfect flux expulsion is possible. We also observed B_{sc}/B_{nc} values clearly smaller than unity (down to 0.66), suggesting "flux admission" under certain conditions. These results indicate that a suitably controlled cool down might be possible for maximizing flux expulsion or minimizing flux admission, thus opening a cost-effective path for improving the quality factor of cavities installed in CEBAF and ultimately saving accelerator operation cost.

INTRODUCTION

Trapped magnetic flux in superconducting niobium cavities is a well-known cause for the residual surface resistance, leading to unwanted heat dissipation at cryogenic temperatures. A large effort has been recently made in pursuit of small flux trapping in SRF cavities for the 4 GeV CW SRF linac in LCLS-II. One outcome of that effort is to push cavity heat treatment temperatures beyond the standard 800 ºC for EXFEL and ILC R&D cavities.

Our CW SRF twin linacs in CEBAF provide acceleration for a beam energy up to 12 GeV by circulating electron bunches. Each 1.1 GeV linac consists of 160 original 5-cell cavities (C20) and 40 new 7-cell cavities (C100). Large cryogenic cooling is needed. CEBAF cavities are made from high purity niobium similar to that for E-XFEL, ILC R&D and LCLS-II. However, there are differences in the post-fabrication hydrogen outgassing heat treatment in a vacuum furnace (see Table 1). Current effort driven by LCLS-II has resulted in an increase in the post-fabrication heat treatment temperature, now typically at 900 ºC, i.e. well beyond the standard 800 ºC. The benefit seems to be associated with metallurgical effects (such as grain growth) brought about at higher temperatures. From that point of view, one may expect our CEBAF cavities to trap ambient flux in entirety, as a result of their 600 ºC heat treatment being ineffective for the said benefit.

The work presented here was initially carried out to verify that expectation. A surprising anomaly was observed after a few tests. It then triggered our effort into systematic studies. Deviations from complete flux trapping are observed, including large flux expulsion under certain conditions and "opposite" flux expulsion under other conditions. 131 cool down cycles were completed, corresponding to nearly 1000 cell-cycles. Detailed analysis of the results are still ongoing, in this contribution we will provide a preliminary report.

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Table 1: Cavity Heat Treatment Parameters

Machine	Temperature [ºC]	Duration [h]
CEBAF C20	No heat treatment	N/A
CEBAF C100	600	10
EXFEL	800	3
LCLS-II	800-995	3

EXPERIMENTAL

The measurement setup is illustrated in Fig. 1. Cryogenic single-axis fluxgate magnetometers are attached to equators with the sensor axis in parallel with the cavity axis as was done in Ref. [1,2]. Temperature sensors are attached next to magnetometers and cavity ends. The cavity is supported in a cage with beam tube ports covered with aluminium foils. Styrofoam inserted between the cavity beam tube and the holding bracket breaks the electrical loop circuit. This completely eliminates magnetic fields generated by the thermal currents during the cool down process.

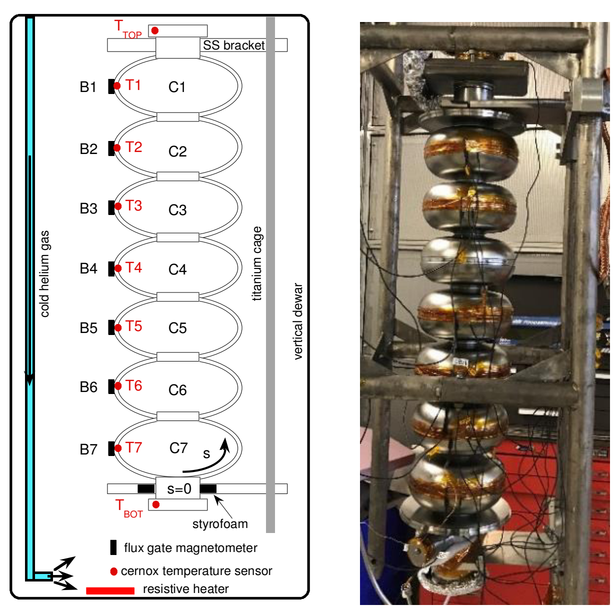

Figure 1: Sketch (L) & photo (R) of measurement setup.

The instrumented cavity is inserted in a vertical dewar (D4) in JLAB's Vertical Test Area. The ambient magnetic field is controlled by adjusting the excitation current of a pair of coils wrapped around the dewar's OD. The ambient

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field as generated in this way is predominantly orientated in the vertical direction (or axial direction of the cavity). Its amplitude is dependent on the penetration depth from the top of the dewar (the deeper the smaller). The typical value for the bottom cell (Cell#7) and top cell (Cell#1) is 7 and 20 mG, respectively. Activities generating rapid disturbances on measured magnetic flux densities, such as overhead crane movements, nearby dewar radiation shield movements, and nearby LCLS-II cryomodule degaussing in the cryomodule testing cave, must be controlled. Slow disturbances due to the chilling of the passive mu-metal shield is mitigated by blowing air around the dewar deck with air circulation fans. Three C100 7-cell cavities and two CEBAF 5-cell cavities have been measured (Table 2).

Table 2: Cavities and Number of Test Cycles

Cavity	Type	Material Supplier	# Cycles
RI009	C100	Tokyo Denkai	44
RI024	C100	Tokyo Denkai	50
PJN7-1	C100	Ningxia OTIC	19
C5-1 & -2	C20	*	18

* Niobium materials for original CEBAF cavities were supplied by Heraeus, Teledyne Wah Chang, and Fansteel

The flux expulsion efficacy is indicated by the quotient of two experimentally observed quantities B_{sc} & B_{nc}, referred to as the Posen Quotient (PQ) hereafter, following Posen [2]. The theoretical limiting PQ values are 1 for complete trapping and 1.23 and 1.35 for perfect expulsion in mid- and end-cells, respectively. The latter are calculated numerically (Fig. 2). More details on our calculations can be found in Ref. [3], i.e. a somewhat higher maximum PQ of 1.23 is found than plotted in Fig. 2 when accounting for the weld preparation machining steps on cell equators and averaging values over the sensitive core of the magnetometer some distance away from the cavity surface. The upper bound of the theoretical value for perfect expulsion is 1.25 for the case where no weld prep is present.

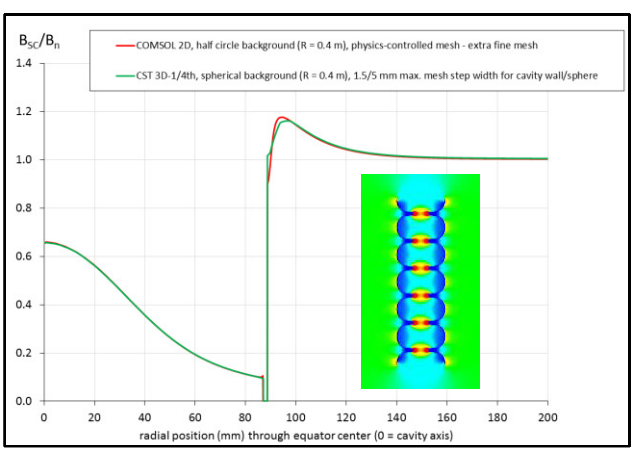

Figure 2: Calculated result for ideal flux expulsion in a C100 cavity. The model is shown in the inset.

The cavity cool down is regulated by adjusting the JT valve opening on the D4 LHe supply line and warm up is regulated by adjusting the drive current of a resistive heater at the bottom of the dewar. Cooling down with the heater off produces a condition in which the bottom end of the cavity is always colder than its top end. As a result, there is a single superconducting phase front and it moves upward. The PQ is the average of two measured values both during cool down and warm up across Tc.

The controlling parameter for our measurements is the spatial temperature gradient along the curved cavity wall (see Fig. 1) at the location of the magnetometer for the instant of the phase front arrival, dT/ds. The procedure for finding this value is given in Ref. [4]. It is based on the local cool down rate dT/dt and the phase front movement speed υ_c. The range of dT/dt and υ_c covered in our measurements is 6×10^{-4} – 1×10^{-1} K/s and 0.2 – 4 mm/s, respectively, resulting in a dT/ds in the range of 10^{-1} – 10^{2} K/m.

RESULTS

Measurement results of two C100 cavities RI009 & RI024 are shown in Fig. 3 (a) & (b), respectively. Typical error bars are shown for one data series in each plot for clarity. The theoretical limiting values for perfect flux expulsion in a mid-cell and end-cell and complete trapping are indicated as well. As can be seen, for some cavity cells (such as RI009 Cell#1,3,7 and RI024 Cell#7), PQ is rather insensitive to dT/ds and its value is close to unity, or almost complete flux trapping regardless of cool down conditions. This case confirms the initial expectation for 600 ºC heat treated high purity fine-grain niobium cavities.

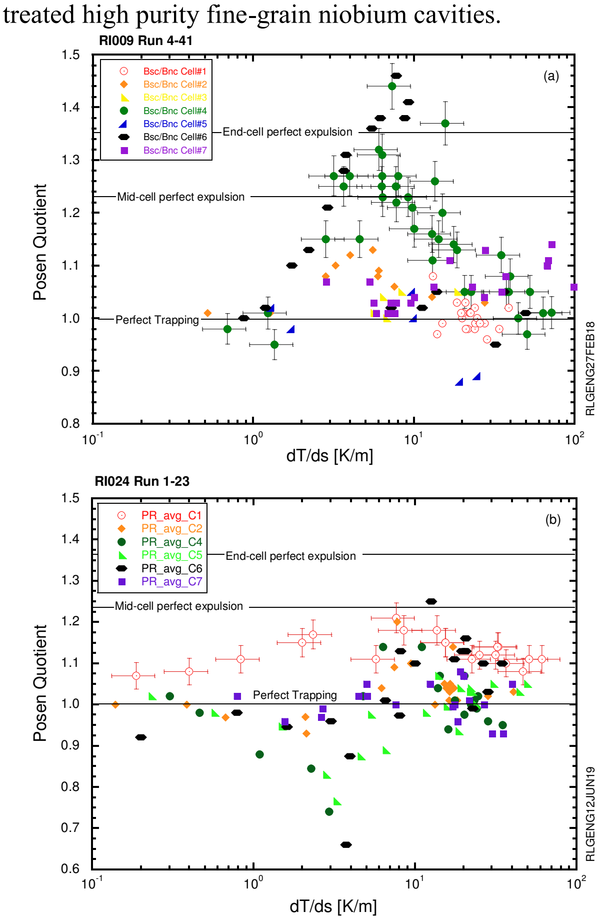

Figure 3: Posen Quotient as a function of spatial temperature gradient at location of measurement.

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Contrary to our initial expectation, large departure in PQ from unity is observed. One the one hand, PQ exhibits strong dependence on dT/ds for some cells (RI009 Cell#4, 6 and RI024 Cell#1,2,4,5,6), with its peak values in this case approaching to and even exceeding the theoretical limit of 1.23; On the other hand, PQ values clearly below unity are observed quite often, an extreme case being 0.66 for Cell#6 of cavity RI024. For both cavities, there is an optimal dT/ds at 10±3 K/s for maximal PQ.

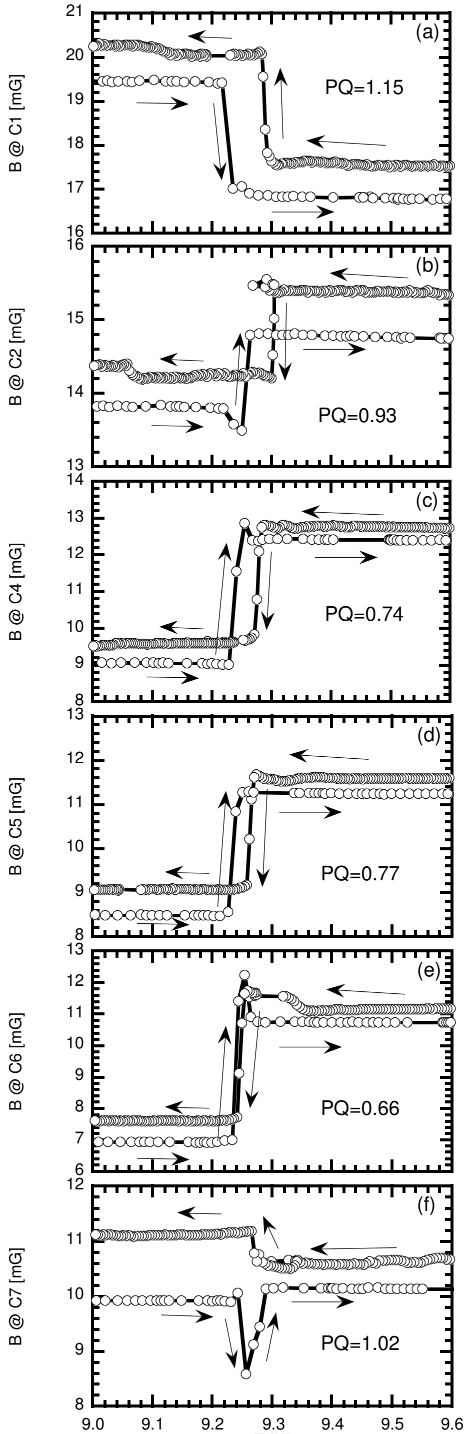

Figure 4: Dependence of local flux density on temperature during cool down & following warm up of RI024 (Run 5).

DISCUSSION

A complete understanding of flux trapping in SRF niobium cavities cooled in a weak ambient magnetic field is still lacking. Our experimental observation of Posen Quotients outside of the lower and upper bounding values corresponding to the case of complete trapping or perfect expulsion seems to offer a new opportunity for probing the dynamic process.

Flux Admission (PQ < 1)

Figure 4 shows the dependence of the local magnetic flux density on the corresponding local temperature for monitored cells (6 out of 7) of RI024 during its 5th cool down and following warm up.

While the behaviour of cell#1 in Fig. 4(a) is consistent with partial flux expulsion, cell#2, 4, 5, and 6 in Fig. 4(b), (c), (d), and (e) show just the "opposite" of flux expulsion. Cell#6 registered a record low PQ value of 0.66. Probing at Cell#4 with clustered magnetometers (wall to wall space about ¼ inch between the nearest sensors) attached around the original magnetometer at that cell (see Fig. 5) revealed flux density decreasing at all four probes upon cooling down across Tc (all being reversed upon subsequent warm up across Tc). This proves that the ambient flux is moving toward, as opposed to away from, the cavity wall. Therefore, we are observing for the first time "flux admission". It should be mentioned that Run 5 of cavity RI024 was cooled down with very small JT opening, resulting in slow cool down and small (~ 4 K) temperature difference from the top to bottom end of the cavity.

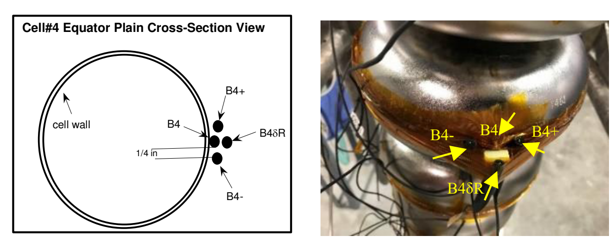

Figure 5: Clustered magnetometers at Cell#4 of RI024.

PQ > 1.23 and Possible Explanation

The observation of a PQ > 1.23 for mid-cells, the theoretical value for homogeneous perfect flux expulsion, is not fully understood. Our calculations have taken care of detailed geometries of the equator region and averaging over the sensitive volume of the magnetometer. We also benchmarked our calculation procedure with a LCLS-II 9-cell cavity model and obtained a theoretical value of 1.39 for perfect expulsion, literally identical to that obtained by Posen, which is 1.4 [5].

We should mention a notable difference in the ambient magnetic field between our calculations and measurements. It is homogeneous for the former and non-uniform for the latter. However, as we know from numerous measurements that the flux expulsion is a "local" event near the phase front. It is not expected that a non-uniformity in B_{nc}

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over the cavity length (or its major radius) has any role in the observed anomaly.

It should be also mentioned that the theoretical calculation is done with the assumption of homogeneous expulsion, which might be not true in reality. This effect is numerically modelled for our C100 cavity to reveal the picture of uneven flux expulsion from cell to cell by assigning cell-dependent relative permeability μ_r. An example is given in Fig. 6. In this case, the μ_r value assigned for the cells are different as shown in Fig. 6(a). Perfect trapping and expulsion is modelled by a μ_r value of 1 and 10^{-6}, respectively. The Cell #4&6 represent perfect expulsion, while Cell #1,3,5,7 nearly perfect trapping, and Cell#2 in between. This model is subjected to a uniform externally applied magnetic field. The resulting field map is shown in Fig. 6(b).

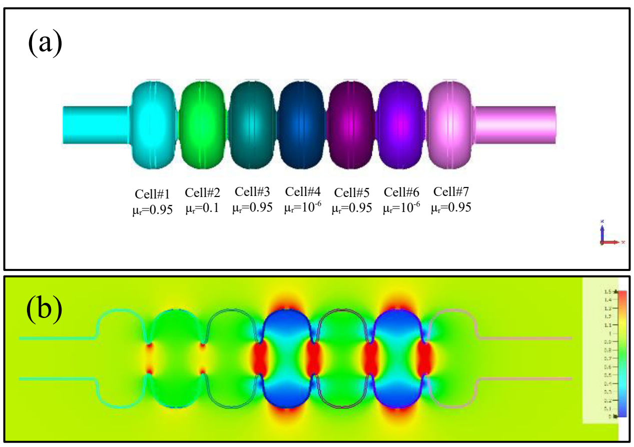

Figure 6: Model and result of cell-to-cell inhomogeneous flux expulsion.

Figure 7 gives the results for four cases: “Case 1” for homogeneous perfect flux trapping; “Case 2” for homogeneous perfect flux expulsion; “Case 8” for inhomogeneous expulsion corresponding to the model in Fig. 6; “Case 13” for another inhomogeneous expulsion model.

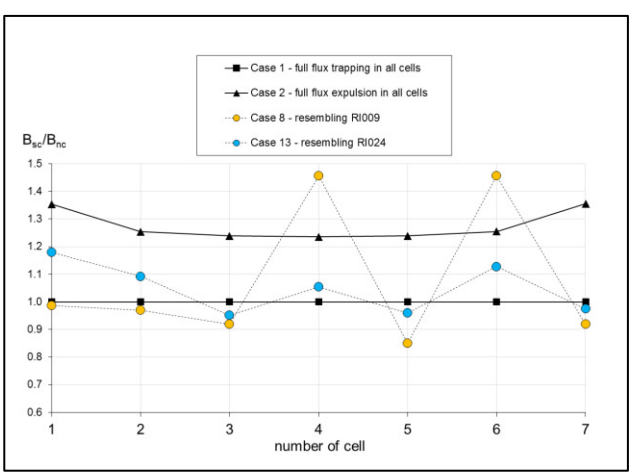

Figure 7: Calculated PQ in each cell of a 7-cell C100 cavity for perfect homogeneous trapping (Case 1), perfect homogeneous expulsion (Case 2), and different models of cell-to-cell homogeneity in flux expulsion (Case 8 & 13).

For Case 8, the PQ for Cell#4&6 is ~ 1.46, exceeding 1.23 which is the value for homogeneous perfect expulsion in every cell. This is quite close the measurement results for cavity RI009 shown in Fig. 3(a). Inhomogeneous expulsion is therefore a possible reason for PQ > 1.23 in the mid-cells. PQ values less than unity is also borne out for Case 8 as well as Case 13.

Theoretical PQ values in our current analysis are calculated with a static field and fixed material property. In our experimental measurements, the cool down is a dynamic process with a moving phase front separating the cavity wall below it that is in superconducting state from that above it in normal conducting state. Therefore, these models with assigned cell-to-cell inhomogeneous μ_r are not realistically matched to the experimental situations. A time-domain calculation would be preferable for future simulation studies.

An alternative explanation to the observed anomaly is that a more fundamental mechanism may be at play near the phase front. For example, a flow of fluxes driven by the pinning force in the azimuthal direction just before the local fluxes are expelled, hence raising the observed B_{sc} beyond that corresponding to the theoretical value for a given B_{nc}, or a PQ value exceeding the theoretical value that is calculated assuming homogeneous expulsion. A complete understanding has to wait until further studies.

It is noted that the theoretical value for perfect expulsion from a single-cell is much larger than for a multi-cell of the identical shape. In case of our C100 cavity, it is 1.54 and1.48 for a mid-cell with and without beam tubes, respectively. The fact that the theoretical PQ is dependent on the geometry and cell numbers makes it obscure for material studies with different cell shapes or numbers. This situation leads to a natural need for a measure to indicate the absolute flux expulsion efficacy. In fact, a normalization technique is available for this [6] and it is to be adopted for our future analysis.

Angular Spread in PQ

Briefly, we want to mention the observation of angular spread in PQ. The measurements are carried out with three magnetometers attached to the equator of the same cell, 90 degree apart. Each magnetometer is accompanied with a temperature sensor. Two cells are instrumented in this fashion for each cool down run. Tests confirm that there is always a fairly uniform temperature angular distribution near 9.25 K. The measured PQ, however, typically has an angular spread well above the measurement uncertainty. For example, over 6 cool down cycles, Cell#1 of cavity RI024 exhibits an average spread of 13%, with a minimum and maximum value of 7% and 19%, respectively; Cell#4 an average spread of 26%, with a minimum and maximum value of 10% and 61%, respectively.

Cool Down Speed dT/dt

The spatial temperature gradient dT/ds is correlated with the local cool down speed dT/dt. Figure 8 shows an example for the cavity RI024. Trifurcation for dT/dt < 3×10^{-3} K/s is resulted from cooling with heater being on or off. Similar

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correlation is observed for cavity RI009. In view of the characteristics of PQ(*dT/ds*) in Fig. 3(b), it becomes apparent that in practical terms neither "fast" nor "slow" cool down is desired for maximal flux expulsion in C100 cavities. A "goldilocks" cool down is to be applied.

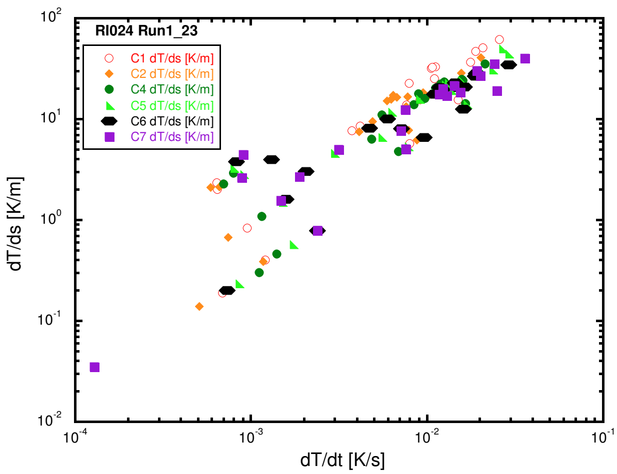

Figure 8: Correlation between local spatial temperature gradient and local cool down speed.

CONCLUSION

We presented results on measurements of flux expulsion in CEBAF 12 GeV upgrade cavities that were made from high purity fine-grain niobium and were heat treated in vacuum at 600 ºC. An optimal thermal gradient ~10 K/m is observed at which flux expulsion is maximal in some cells. The maximal value of Posen Quotient reaches or exceeds the theoretically calculated limit, suggesting perfect flux expulsion is possible. Posen Quotient values clearly smaller than unity, as low as 0.66, are observed. Probing with clustered magnetometers suggests that we are observing "flux admission". These results indicate that a suitably controlled cool down might be possible for maximizing flux expulsion or minimizing flux admission, thus opening a cost-effective path for improving the quality factor of cavities installed in CEBAF and ultimately saving accelerator operation cost.

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